

# $\nu$ masses in a SUSY SO(10) theory with spontaneous CP violation

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We propose a possibility of spontaneous CP-violation (SCPV) at high scale in a SUSY SO(10) theory. The model is L-R symmetric SUSY SO(10) with **10** and **126** dimensional Higgs generating fermion masses, and the CP phase is generated through complex VEV of B-L breaking **126** Higgs. The model can have potential application in explaining  $\nu$  masses and leptogenesis as well.

## I. INTRODUCTION

CP violation (CPV) was discovered experimentally about four decades ago, but its origin still remains one of the fundamental open question in particle physics. CPV is directly observed only in the decays of the Kaons and B-mesons. At least four aspects of CPV are observed in nature — CPV in quark sector [1,2], in lepton sector, generation of BAU (baryon asymmetry of the Universe), and strong and SUSY CP problems. In this paper, we address its manifestation in the first three cases only.

Within the premises of the standard model (SM) model, neutrinos are mass-less, so there is no mixing and no CPV in the neutrino sector. However, the existence of  $\nu$  masses is a well established fact now, and hence any theory which can explain them would also imply CPV in leptonic (CPV-L) sector in principle. The latter might be detected in future experiments to be performed at neutrino factories. Indirect evidence for the CPV-L may also be provided by forthcoming experiments on  $\nu$ -less  $\beta\beta$  decay (Majorana phases). Existence of matter dominated Universe is another evidence of CPV, but it has been established that within the SM, it is not possible to generate observed BAU, partly due to smallness of CPV in SM (CKM phase). This provides motivation for considering new sources of CPV beyond the SM-CKM mechanism (e.g. through CPV from SUSY breaking sector). In gauge theories, there are two possibilities of CPV — explicit (hard) CP breaking at the Lagrangian level through complex Yukawa couplings (as in SM), or spontaneous (soft) CP breaking by the vacuum via complex VEV of the Higgs (SCPV).

SCPV at higher scales seems to be an interesting proposition to explain the origin of CPV in nature since all the couplings of the Lagrangian are real due to CP invariance at the Lagrangian level. CP is broken only through phases in VEV of the Higgs [3,4]. There has been significant amount of work in literature addressing the question of SCPV, an incomplete list is given as [5-10]. It has been a known difficulty with SUSY theories that they cannot generate CP breaking spontaneously. This is because they lead to a real CKM matrix. A recent analysis [11] of the present experimental data provides clear evidence for a complex CKM matrix. These experimental findings [12] of the angle  $\gamma$  inspires to ask the question if we can have a SUSY extension of the SM with SCPV and a complex CKM matrix. In fact some work has already been done in this line [6-9]. There, they introduce extra vector-like quark which mixes with standard quarks and leads to a non-trivial phase in  $3 \times 3$  CKM matrix [7], VEV of **126** Higgs in SUSY SO(10) theory is complex [6], or add extra Higgs [8], extension of SM with a  $SU(2)_L$  singlet quark and a singlet Higgs field [10], has been considered.

## II. MOTIVATION FOR THE PRESENT WORK

In the present work, we have attempted to find a possible model to generate a CP phase spontaneously in L-R symmetric SUSY SO(10) theory, in particular in context of generating neutrino masses and mixings. In the framework of SO(10) GUT SCPV was first discussed in [13]. In the present model, B-L symmetry is broken by a **126** dim Higgs, which also contributes to fermion masses along with a **10** dim Higgs [14,15]. This theory seems to be too attractive to generate small  $\nu$  masses — it has a right handed Majorana neutrino (RHMN) to implement see-saw mechanism, naturally contains B-L symmetry needed to keep the RHMN below the Planck scale, provides a group theoretical explanation of why neutrinos are Majorana particles, has automatic R-parity conservation which leads to natural conservation of baryon and lepton number symmetry prior to symmetry breaking, provides a simple mechanism for explaining origin of matter in the Universe etc. It has been shown that type-I see-saw predictions of this model are in contradiction with experiments [14,16]. Then, type-II see-saw [17] for neutrino masses [18] was suggested to

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explain the data. In [19]  $b - \tau$  unification was used to explain the  $\nu$  masses and mixings. In [20], CPV was introduced through complex Yukawa couplings (of course this list is incomplete!), and it was found that compatibility with  $\nu$  data requires CKM phase to be outside the first quadrant (whereas the SM CKM phase is in first quadrant). It implies that to understand CPV in this minimal SO(10) model, one must have a non-CKM source for CPV. So it would be interesting to see how CPV can be generated in this model to explain  $\nu$  masses and mixings, along with generation of BAU through leptogenesis with the minimal modification. Attempts have already been made in this direction [21,22], but they included **120**-dim Higgs and CP is violated through complex Yukawa couplings.

In the present work, we propose a different scenario. We show that if assume SCPV at higher scales in minimal SUSY SO(10) theory with complex VEV for B-L breaking **126** Higgs, one can't have a nontrivial CPV phase. So we propose that if we include two **126** Higgs, one with a real VEV and the other with a complex VEV, one can have a nontrivial value of CPV phase by some fine-tuning in the Higgs coupling constants of the Lagrangian. Now since the theory has  $SU(4)_C$  symmetry at higher scales, the CKM phase in the baryonic quark mass matrix will be related to CP phases in the leptonic sector as well. And since heavy RH Majorana neutrino mass matrix will be complex (due to complex VEV of **126** Higgs) the model has the potential to explain BAU also. But, we would like to stress that we are not attempting to comment on other issues such as strong CP, SUSY CP problems etc, which can be solved may be by imposing some additional symmetries on the Lagrangian, or via some other mechanism. This lies beyond the scope of this paper.

Now, we would like to present the distinguishing features and novelties of our work, as compared to some of the recent works in this line:

1. In [21,22], CP is introduced through complex Yukawa couplings, whereas we use SCPV.
2. In [9], SUSY SO(10)  $\rightarrow$  SM via intermediate SU(5), while here we have used  $SU(2)_L \times SU(2)_R \times SU(4)_C$  as the intermediate symmetry, although the breaking is single step (i.e.  $M_U = M_R$  [15]).
3. In [8], they add extra Higgs/Higgs+fermions to the SM, while here we have added extra **126** Higgs to the SUSY SO(10) theory, with VEV of one of the **126** as real, and that of the other as complex. At the same time, we have applied it for specific model building purpose (for neutrino masses).

### III. THE MODEL

We consider the SUSY SO(10) theory, with **45(A)+54(S)** dim Higgs field breaking SO(10) down to the L-R symmetric group  $SU(2)_L \times SU(2)_R \times U(1)_{(B-L)} \times SU(4)_C$  ( $G_{2213}$ ), and the minimal Higgs set  $10 + 126 + 1\bar{26}$  that couple to matter and also break the  $G_{2213}$  group to  $G_{31}$  ( $SU(3)_C \times U(1)_{em}$ ) [15] (these details are well established, but for the sake of completeness, we shall review them briefly here). The Majorana mass of heavy RH neutrino owes its origin to the breaking of local  $B - L$  symmetry, therefore  $M_R \sim M_{\text{seesaw}} \sim M_{B-L}$  [23]. Local  $B - L$  symmetry provides a natural way to understand smallness of RH neutrino mass compared to  $M_{Pl}$ . With  $G_{2213}$  one can understand parity violation in nature. **126** ( $\Delta$ ) leaves R-parity as an exact symmetry, and explains why neutralino can act as stable dark matter candidate [24]. In a generic SO(10) with **126** getting VEV, one gets two contributions to  $\nu$  masses - type-I see-saw and type-II see-saw (from induced VEV of the triplet Higgs). The superpotential also contains Planck scale induced non-renormalisable terms (more than dim-3), to give induced VEV to triplet of **126** (for type-II see-saw). If these are not included, **210** Higgs is needed, but getting DTS is not very simple [25] here. The superpotential of the theory contains three parts,

$$W = W_f + W_s + W_p, W_f = h_{ab} \Psi_a \Psi_b H + f_{ab} \Psi_a \Psi_b \bar{\Delta}, \quad (1)$$

where  $W_f$  generates mass of matter, with (2,2,1) of **10** dim H and (2,2,15) of **126** dim Higgs acquiring VEV,  $\Psi$  is the 16-dim spinor (matter field) of SO(10). The  $W_s$  contains scalar Higgs contribution, and is

$$W_s = (\mu_H + \lambda S) H H + \mu_s S^2 + \lambda_s S^3 + \mu_A A^2 + \mu_\Delta \Delta \bar{\Delta} + \lambda_\Delta \Delta A \bar{\Delta} + \lambda'_s (S \Delta \Delta + S \bar{\Delta} \bar{\Delta}) + \lambda_A S A^2. \quad (2)$$

The  $W_p$  is Planck-scale induced part of the superpotential

$$W_p = \frac{\sqrt{8\pi}}{M_{Pl}} \lambda_P \Delta A^2 H. \quad (3)$$

Now, from the superpotential, the F-term (Higgs part) of the potential can be constructed as  $V = \sum_i \left| \frac{\partial W}{\partial \sigma} \right|^2$ , where  $\sigma$ s are the Higgs scalars,

$$V = \left| \frac{\partial W}{\partial \Delta} \right|^2 + \left| \frac{\partial W}{\partial \bar{\Delta}} \right|^2 + \left| \frac{\partial W}{\partial S} \right|^2 + \left| \frac{\partial W}{\partial A} \right|^2 + D - \text{term}, \quad (4)$$

and it is easy to see that  $\langle A \rangle \Delta \Delta \bar{\Delta} H$  term from  $\left| \frac{\partial W}{\partial A} \right|^2$  will contribute induced VEV to  $\Sigma(2, 2, 15)$  of 126 Higgs, to correct mass relations of fermions, while  $\Delta \Delta H H$  from  $\left| \frac{\partial W}{\partial S} \right|^2$  term will contribute induced VEV to triplet  $\Delta_L(3, 1, \bar{10})$  for type-II see-saw mechanism.

Next, we shall consider how the breaking of higher symmetries is realized through VEVs of Higgs along different directions. In a SUSY theory, the ground state should have zero energy, so both F-flatness and D-flatness conditions must be satisfied. The latter is ensured by the presence of both  $\Delta$  and  $\bar{\Delta}$ . The F-flatness conditions, with the scalars acquiring VEVs as follows are

$$\langle S \rangle = \text{diag}(k, k, k, k, k, k, k', k', k', k'), \langle A \rangle = i\tau_2 \times \text{diag}(b, b, b, c, c), \quad (5)$$

$$\langle \Delta \rangle = v_R e^{i\delta}, \langle \bar{\Delta} \rangle = v_R e^{-i\delta}, \quad (6)$$

$$F_s : \frac{\partial W}{\partial k} = 2\mu_s k + 3\lambda_s k^2 + \lambda'_s (x_0 v_R^2 e^{2i\delta} + x_0 v_R^2 e^{-2i\delta}) - \lambda_A b^2 = 0, \quad (7)$$

$$\frac{\partial W}{\partial k'} = 2\mu_s k' + 3\lambda_s k'^2 + \lambda'_s (v_R^2 e^{2i\delta} + v_R^2 e^{-2i\delta}) - \lambda_A c^2 = 0, \quad (8)$$

$$F_A : \frac{\partial W}{\partial b} = -2b\mu_A + \lambda_\Delta x_0 v_R^2 - 2b\lambda_A k = 0, \quad (9)$$

$$\frac{\partial W}{\partial c} = -2c\mu_A + \lambda_\Delta v_R^2 - 2c\lambda_A k' = 0, \quad (10)$$

$$F_\Delta = \mu_\Delta v_R e^{-i\delta} + \lambda_\Delta (x_0 b + c) v_R e^{-i\delta} + 2\lambda'_s (y_0 k + k') v_R e^{i\delta} = 0, \quad (11)$$

$$F_{\bar{\Delta}} = \mu_\Delta v_R e^{i\delta} + \lambda_\Delta (x_0 b + c) v_R e^{i\delta} + 2\lambda'_s (y_0 k + k') v_R e^{-i\delta} = 0, \quad (12)$$

where  $x_0$  and  $y_0$  are appropriate C-G coefficients, due to involvements of different groups. These constraints must give a non-trivial solution for the CPV phase  $\delta$ . The  $F_\Delta$  and  $F_{\bar{\Delta}}$  constraints can be written as

$$(A + B) \cos \delta + i(A - B) \sin \delta = 0, \quad (13)$$

$$(A + B) \cos \delta + i(B - A) \sin \delta = 0, \quad (14)$$

where constants  $A$  and  $B$  involve various Higgs couplings and VEVs etc. It is easy to see that these equations give only the trivial solutions  $\delta = 0$  and  $\delta = \pi/2$ . These values of  $\delta$  have also to be satisfied simultaneously by the  $F_s$  constraints,

$$F_{s_k} : \cos 2\delta = \frac{\lambda_A b^2 - 2\mu_s k + 3\lambda_s k^2}{2\lambda'_s x_0 v_R^2}, \quad (15)$$

$$F_{s_{k'}} : \cos 2\delta = \frac{\lambda_A c^2 - 2\mu_s k' + 3\lambda_s k'^2}{2\lambda'_s v_R^2}. \quad (16)$$

Eqs. (13-16) are the new results of our present work, which implies that one can not have a nontrivial value of the CPV phase in a L-R symmetric minimal SUSY SO(10) theory, where CP has been broken spontaneously at high scale by the complex VEV of **126** Higgs.

### A. New proposal

To overcome this difficulty, therefore, we propose that in the model, we have two **126** Higgs,  $\Delta_1$  and  $\Delta_2$ , such that one of them acquires a real VEV while the other one a complex VEV,

$$\langle \Delta_1 \rangle = v_R e^{-i\delta}, \langle \Delta_2 \rangle = \epsilon v_R, \quad (17)$$

here  $\epsilon$  is a fine tuning parameter, which can be adjusted to get a desired nontrivial value of CPV phase at higher scales [see Eqs.(15-17)]. Note that this is not possible in a theory with one **126**, or with two **126**s with same VEVs

(real or complex). The terms of the Lagrangian involving products of the form  $\Delta_1\Delta_2$  will help us get values of CPV phase other than 0 or  $\pi/2$ , through the structure of Eqs. (13-16). The part of the new superpotential generating fermion masses will look like,

$$W_f = h_{ab}\Psi_a\Psi_b + f_{1ab}\Psi_a\Psi_b\bar{\Delta}_1 + f_{2ab}\Psi_a\Psi_b\bar{\Delta}_2, \quad (18)$$

and accordingly, one can have new formulas for neutrino masses. Since the VEV of a **126** is complex, the fermion mass matrices, the CKM matrix and the heavy right handed Majorana mass matrix will be complex.

#### IV. CONCLUSIONS

To conclude, we have presented a novel mechanism of generating CP violating phase spontaneously at higher scales in a L-R symmetric SUSY SO(10) theory, which can be further applied in context of neutrino masses and mixings, and leptogenesis. Eq. (17) is the new idea proposed here for the first time, in this work, which together with Eqs. similar to (13-16) can give a nontrivial CP violating phase (other than 0 or  $\pi/2$ ) in the theory. We have shown this explicitly through the F-flatness conditions. Of course further investigations, as far as the applications and implications of this idea are concerned, are needed, which can be taken up in future works.

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